

PATENT APPLICATION

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Title: Thin Film Solar Cell Inflatable Ultraviolet
Rigidizable Deployment Hinge

SPECIFICATION

Statement of Government Interest

The invention was made with Government support under
contract No. NAS3-01115 by NASA. The Government has certain
rights in the invention.

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Field of the Invention.

The invention relates to the field of thin film solar cell devices, manufacturing methods, and deployment means. More particularly, the present relates to the structure and fabrication processes for the formation of inflatable hinges for deployment of thin film solar cells for the collection and distribution of the collected solar power.

Reference to Related Application

The present application is related to a copending application entitled Thin Film Solar Cell Electrical Contacts, S/N: xx/xxx,xxx, filed yy/yy/yy.

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Background of the Invention

US Patent 6,127,621 entitled Power Sphere, US Patent 6,284,966 entitled Power Sphere Nanosatellite, US Patent 6,396,167 entitled Power Distribution System, US Patent 6,318,675 entitled Power Sphere Deployment Method, and US Patent 6,300,158 entitled Integrated Solar Power Module, all of which are hereby incorporated by reference, teach the use of solar cells for powering a spacecraft. The connections between individual serially connected solar cells and serial strings of solar cells have been accomplished by soldering or welding interconnect conductors to the front and back contacts of the solar cells. Solar cells use wire or wire mesh interconnects to connect individual solar cells in a series or to serially connect strings of solar cells to a spacecraft power bus. However, solder and mesh interconnections disadvantageously add significant mass to the thin film structure.

Thin film solar cells can be fabricated using monolithically integrated interconnections that eliminate the need for separate interconnect conductors for connecting a string of solar cells in series. Monolithically interconnected serial strings of thin film solar cells are readily available in commercial markets. Conventional thin film solar cells can be monolithically interconnected in thin film solar cell modules, but ultimately require connection to the spacecraft power bus disadvantageously using welding or soldering interconnects between the module and the power bus. The

1 interconnects are typically made by soldering or welding
2 methods to make electrical connections between the solar cells
3 and the power bus. These welding and soldering methods of
4 interconnection are not well suited for sensitive thin film
5 structures due to excessive spot heat. That is, welding or
6 soldering requires a high temperature to melt the solder or to
7 weld a contact. This high temperature may be significantly
8 higher than the maximum temperature that the thin film solar
9 cell can withstand without damage during fabrication. Hence,
10 another problem of connecting monolithically integrated thin
11 film solar cells is the use of hot welding and soldering
12 methods for interconnecting the thin film solar cells to the
13 spacecraft power bus.

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15 US Patents 6,284,966, and 6,318,675, and 6,127,621 teach
16 stowing and deploying a stack of hexagons and pentagons to form
17 a geodetic sphere as a power sphere spacecraft. The flat
18 hexagonal and pentagonal panels are thin film solar cell panels
19 that form a power sphere. Inflatable hinges are flexible
20 tubular hinges used to precisely position the individual panels
21 from a stowed position into final deployed positions forming
22 the sphere of panels. One problem associated with flexible
23 inflatable hinges is the need for routing power produced by the
24 thin film solar cell panels across the hinges to the power bus.

25
26 The inflatable hinges are flexible for enabling inflation
27 using sublimation powders for deploying space structures. The
28 inflatable hinges do not form a rigid structure after the

1 deployment is complete. It is desirable to rigidize the
2 positions of the panels for accurately and rigidly forming the
3 power sphere. Mechanical hinges can be used for rigidizing the
4 position of the panels after deployment. However, mechanical
5 deployment hinges disadvantageously add significant mass and
6 control complexity to the spacecraft. Also, electrical
7 conductors that cross the hinges are bundled together causing
8 twisting and stresses that may lead to breakage of the
9 conductors. Also, mechanical hinges disadvantageously require
10 variable sizes to accommodate variable stacking thicknesses of
11 the panels. These and other disadvantages are solved or reduced
12 using the invention.

Summary of the Invention

An object of the invention is to provide wrap around contacts for connecting a thin film solar cell to a flex circuit.

Another object of the invention is to provide wrap around contacts for connecting a thin film solar cell to a flex circuit using laser welding.

Yet another object of the invention is to provide a flexible inflatable hinge for rigidly positioning solar cell panels.

Still another object of the invention is to provide a flexible inflatable hinge for rigidly positioning solar cell panels and for interconnecting solar cells to a system power bus through flex circuits.

A further object of the invention is to provide a flexible inflatable hinge for rigidly positioning solar cell panels and for interconnecting the hinge to system ground bus through flex circuits.

In a first aspect, the invention is directed to a wrap around contact for providing electrical connections between a thin film solar cell contact and electrical conductors in a flex circuit for routing electrical energy produced by the

1 solar cells to a power bus. The wrap around contact fabrication
2 method forms electrical connection between the current
3 collecting conductors of a monolithically interconnected thin
4 film solar cell panel and a flex circuit used for routing a
5 power conductor and a ground conductor from the solar cells.
6 The wrap around contact is preferably made of copper for
7 conducting electrical current.

8
9 In a second aspect, the invention is directed to a
10 flexible inflatable hinge that includes curable resin for
11 rigidly positioning panels of solar cells about the hinge at
12 precise angular displacements from each other. In the preferred
13 form, the wrap around contact and flex circuit are disposed in
14 the hinge for routing power from the solar cells to external
15 power conversion electronics. A transparent coating is used to
16 prevent static discharge while being transparent to ultraviolet
17 light that cures the embedded curing resin for rigidizing the
18 inflatable hinge after deployment. The flex circuit is also
19 preferably routed to a plurality of ground pads for electrical
20 grounding the inflatable hinge at various locations about the
21 hinge to prevent static discharge. These and other advantages
22 will become more apparent from the following detailed
23 description of the preferred embodiment.

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Brief Description of the Drawings

Figure 1A is a diagram of top contact deposition.

Figure 1B is a diagram of bottom contact deposition.

Figure 1C is a diagram of a contact laser weld.

Figure 2 is flow diagram of a wrap around contact fabrication process.

Figure 3A is a sectional diagram of an inflatable rigidizable hinge.

Figure 3B is a sectional diagram of a grounded inflatable rigidizable hinge.

Figure 4 is a flow diagram of a wrap around contact fabrication process.

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Detailed Description of the Preferred Embodiment

An embodiment of the invention is described with reference to the figures using reference designations as shown in the figures. Referring to Figures 1A, 1B, 1C, and 2, a solar cell panel includes a thin film solar cell having a top silver contact and a polyimide substrate. The electrical connection between the thin film solar cells and the flex circuit is made by depositing a wrap around contact through shadow masks. The wrap around deposition covers in part the top, bottom, and side of the solar cell panel. A top contact made of copper is deposited through a shadow mask on to the edge of the panel covering in part the solar cell silver contact and the side edge of the solar cell panel. After depositing the top contact on the side of the panel, the shadow mask is removed. The panel is flipped and a second shadow mask is installed for depositing a bottom contact made of copper covering in part the polyimide substrate and the side of the top contact, after which the second shadow mask is removed. The bottom contact and top contact form a wrap around contact covering in part the solar cell silver contact, the side edge of the panel, and polyimide substrate.

The flex circuit comprises thin film insulating layers and conductive trace layers that are fabricated one layer at a time. The flex circuit has copper conductor traces. The conductor traces can be etched in the shape of a weld pad. Preferably, the bottom sheet of the flex circuit is a polyimide

1 sheet, for example, a sheet of Kapton, with a portion removed
2 locally around the weld pad. This is accomplished as an initial
3 step during construction of the flex circuit. Once the
4 insulting material is removed from the weld area, a copper film
5 can be bonded to the insulating sheet. The copper film is then
6 etched to create the weld pads and conductor traces. An
7 additional cover polyimide layer, not shown, may also be bonded
8 on top of the flex circuit to cover the conductor traces. Both
9 insulating polyimide layers have the same portion removed
10 around the weld area so that the copper conductor trace is
11 exposed on both sides of the flex circuit for direct welding to
12 the wrap around contact. A laser wire stripper can also be used
13 to specifically remove the portion of the insulating sheet
14 around the weld area.

15
16 The flex circuit having an exposed top conductor trace of
17 copper is then laser welded to the wrap around contact. The
18 laser weld serves to bond the flex circuit to the solar cell
19 panel. The laser weld further serves to electrically connect
20 the top trace of the flex circuit to the wrap around contact
21 and to the solar cell silver contact so as to electrically
22 connect the flex circuit to the solar cell contact. The laser
23 weld is created by focusing a laser beam on the exposed trace
24 that is abutting the wrap around contact in the weld area so as
25 to weld together the top trace and the wrap around contact. The
26 wrap around contact provides power and ground bus connections
27 between silver contacts on the thin film solar cell to flex
28 circuit. The flex circuit is preferably made of a separate

1 sheet of polyimide with etched top copper conductor traces
2 deposited on or bonded to the insulating polyimide sheet. The
3 polyimide sheet can also be formed from several polyimide
4 insulating layers with embedded conductor traces.

5
6 Vapor deposition is used to deposit the top and bottom
7 copper contacts of the wrap around contact on the edge of the
8 thin film solar cell. The flex circuit traces are deposited on
9 or bonded to the polyimide sheet. To provide additional bonding
10 strength, the flex circuit can be adhesively bonded to the
11 solar cell panels. Portions of the polyimide sheet can also be
12 bonded with an adhesive to the back of the thin film solar cell
13 on the polyimide substrate such that the flex circuit trace and
14 the wrap around contact would make a metal-to-metal contact for
15 laser welding. A laser welder would then be used to spot-weld
16 the wrap around contact and the flex circuit top conductor
17 trace for providing an electrical connection. The integrated
18 flex circuit routes power from each solar cell to the
19 spacecraft power conversion electronics, not shown.

20
21 Preferably, the flex circuit is sized or patterned so that
22 the top trace extends past the edge of the polyimide layer. The
23 top trace conductor is then exposed for direct illumination by
24 the laser beam for directly welding the top conductor trace to
25 the bottom side of the wrap around contact. In so doing, the
26 laser does not burn through the polyimide sheet thereby
27 preventing the generation of carbon debris that might otherwise
28 contaminate the laser spot weld between the wrap around contact

1 and the top conductor trace. Various methods can be used to
2 trim the polyimide sheet of the flex circuit so as to expose
3 the top conductor trace. Such methods may include patterned
4 polyimide layer generation, such as patterned holes in the
5 polyimide sheet. Laser wire stripping or mechanical cutting can
6 be used as well for trimming the polyimide layer to expose the
7 top conductor trace for direct laser spot welding.

8
9 Referring to all of the Figures, and more particularly
10 Figures 3A, 3B, and 4, the solar cell panel assembly including
11 the solar cell panel, wrap around contact, and flex circuit can
12 be used in an inflatable rigidizable hinge. The hinge is an
13 elongated hinge extending between the solar cell panels. The
14 hinge is shown in two cross-sectional views for convenience.
15 The hinge can be used, for example, to position two solar cell
16 panels in relative positions to each other. Such hinges and
17 panels can be used to form a power sphere nanosatellite. A left
18 side panel, includes a left thin film solar cell comprising the
19 left solar cell with a left polyimide substrate and with a left
20 silver contact, and includes a left cover layer that is
21 deposited over thin film solar cell. The left panel is laser
22 welded to the flex circuit at a proximal end. A right side
23 panel, includes a right thin film solar cell comprising a like
24 right solar cell with a right polyimide substrate, and a right
25 silver contact, and includes a right cover layer that is
26 deposited over the right thin film solar cell. The hinge is
27 used to relatively position right and left panels while
28 enabling electrical connection from the left panel, through the

1 flex circuit, and along the right panel to the power conversion
2 electronics, not shown. The flex circuit can be a continuous
3 sheet having many parallel traces extending along several
4 panels with respective wrap around contacts for interconnecting
5 the panels to the conversion electronics. As such by one
6 example, the flex circuit is laser welded to the left panel. As
7 such, power and grounds conductors can be routed through the
8 flex circuit for routing power from the solar cell panels.
9 Hence, the flex circuit becomes an integral part of the hinge.
10 The left Frame is shown as top and bottom left frames that are
11 bonded to the left panel. A right Frame is shown as top and
12 bottom right frames bonded to the right panel. The frames are
13 panel supports that resist flexing of the panels during use,
14 and extend around the edges of the respective panels, as well
15 as through the hinge. The flex circuit is disposed between the
16 top and bottom left frames that are bonded together as the left
17 frame, and between top and bottom right frames that are also
18 bonded together as the right frame, for routing and securing
19 the flex circuit to the respective left and right panels within
20 the respective left and right frames. A top film is formed as
21 an overlapped and elongated pocket, running the elongated
22 length of the inflation bladder. A curing resin is disposed in
23 the elongated pocket of the top film. The resin is impregnated
24 with glass fibers for improved strength. Preferably, a sheet of
25 glass fibers is impregnated with a curing resin and inserted
26 into the elongated pocket of the top film. In an uncured state,
27 the resin is inserted and enclosed into the top film that is
28 then thermally sealed. The rigidization curing material in the

1 top film may actually be 449 1250 S-2 glass fibers impregnated
2 with ATI-P600-2 UV curable epoxy resin. The stiffness, strain
3 to failure, environmental resistance, thermal conductivity, and
4 coefficient of thermal expansion are properties considered for
5 the fibers. The coefficient of thermal expansion is important
6 in developing a near zero coefficient of thermal expansion
7 structure that would not suffer shape changes from variable
8 thermal inputs on the structure. Carbon, Kevlar, and Vectran
9 all exhibit low or negative coefficients of thermal expansion.
10 S-glass fibers have a low coefficient of thermal expansion of
11 1.6×10^{-6} ppm/ $^{\circ}$ C. An E-glass fiber has a slightly higher
12 coefficient of thermal expansion 5.4×10^{-6} ppm/ $^{\circ}$ C. The resin has
13 a glass transition temperature of 211° C, well above operational
14 temperatures. The resin can be cured from UV energy from the
15 sun in approximately ten to forty-five minutes depending on
16 shadowing effects, material thickness, and the UV transparency
17 of the top film. The uncured resin is heated, for example by
18 sun light, to at least -20° C prior to curing by UV sun light
19 exposure. The top film is bonded to top left and right frames.
20 A bottom film is then bonded to the bottom left and right
21 frames. The top and bottom films are preferably bonded to the
22 left and right frames using, for example, an adhesive, such as
23 the left and right adhesives disposed between the top left and
24 right frames and the top film. The top and bottom films are
25 flexible films, and form flexible elements of the hinge. The
26 flex circuit is integrated with the thin film solar cell panel
27 and incorporated into the hinge between the bladder and the
28 bottom film.

1 After securing the top and bottom films to the top and
2 bottom of the left and right frames, flex circuit ground
3 extensions are routed to various positions about the top and
4 bottom films for distributed grounding. The flex circuit
5 provides the electrical conduction path for electric power
6 generated by the thin film solar cell, and any associated
7 instrumentation, electronics, or sensors, not shown. The flex
8 circuit also provides the electrical grounding path for the
9 transparent coatings covering the hinge. As shown in Figure 3B,
10 ground pads are deposited on the solar cell panels, such as a
11 left cover pad on the top of the left panel, and a left cell
12 pad deposited on the bottom of the left solar cell of the left
13 thin film solar cell panel. Ground pads are also deposited on
14 the top and bottom films, such as the top pad and bottom pad,
15 as shown. Four flex circuit ground extensions, also made from a
16 polyimide sheet and conductor copper traces, are routed to
17 respective ground pads. The four flex circuit ground extensions
18 are also disposed between the left and right frames for
19 securing the flex ground extensions. The four flex circuit
20 ground extensions include a top pad ground flex circuit
21 extension routed to the top pad on the top film, a bottom pad
22 ground flex circuit extension routed to the bottom pad, a left
23 cover ground flex circuit extension routed to the left cover
24 pad, and a left cell ground flex circuit extension routed to
25 the left cell pad. The flex circuit extension include a ground
26 top trace, not shown, that can be laser welded to a respective
27 ground pad, so as to route electrical ground through the ground
28 bus in the flex circuit to all of the ground pads for

1 distributively grounding of the hinge. A top coating is
2 deposited over the top film and over the left and right solar
3 cell panels. A bottom coating is deposited over bottom film and
4 over the bottoms of the left and right solar cell panels. The
5 top and bottom transparent coatings are transparent to
6 ultraviolet light for curing the resin after deployment of the
7 hinge. The coating is conductive and distributively grounded
8 for preventing electrostatic discharge and build up about the
9 hinge. The coating is conductive and is deposited to make
10 conductive contact with four ground pads so as to
11 distributively ground the top and bottom coatings. The coating
12 is a composite material made of indium tin oxide and magnesium
13 fluoride (ITO/MgF₂). The ITO/MgF₂ transparent coatings provide
14 ultraviolet transparency and electrical conduction about the
15 nonconductive surfaces of the top and bottom films. The ITO/MgF₂
16 top and bottom transparent coatings are UV transparent to allow
17 ultraviolet radiation from the sun to cure the resin once the
18 hinge is deployed. The top and bottom transparent coatings are
19 also transparent to visible light for enabling solar power
20 collection by the thin film solar cells. The ITO/MgF₂
21 transparent coating provides protection from atomic oxygen for
22 polymer based films components. The ITO/MgF₂ coating contains 9%
23 MgF₂ and is preferably at least 500 angstroms thick to provide
24 adequate protection from atomic oxygen erosion of the protected
25 surfaces, yet thin enough to enable UV transparency.

26
27 The top and bottom transparent coatings allow UV sunlight
28 to pass through the coatings and top film in order to cure the

1 curing resin in the desired wavelengths, such as, below 385 nm.
2 To assist in the curing process, it is desirable to have vapor
3 deposited reflective coatings on the bladder. The reflective
4 coatings are preferably made of vapor deposited aluminum. The
5 reflective coatings on the bladder will reflect a percentage of
6 UV light back into the curing resins.

7
8 The top and bottom films have the ability to be packed
9 tightly without tearing or pin holing. The top and bottom films
10 have low permeability to a variety of chemicals. In addition,
11 the films have low elongation properties so that the inflated
12 shape forms to the desired cure shape. The top and bottom films
13 are made of polymer materials that enable thermally welded
14 sealing. Such polymer material may be Mylar and Kynar. Mylar is
15 a polyester film, is UV transmissive, moderately flexible,
16 strong, but at times difficult to thermally weld. Kynar is made
17 from polyvinylidene fluoride (PVDF), is moderately flexible,
18 strong, and can be thermally welded. The polyvinylidene
19 fluoride films are preferred as a UV transparent flexible film
20 that can also be thermally welded. The top and bottom films are
21 preferably made of Mylar LBT-2 or Kynar 740 having strong and
22 reliable welded seams.

23
24 The bladder is preferably made of Mylar MC2 that is coated
25 with a 0.001 inch thick vapor deposited aluminum reflective
26 coating. The coated bladder film is then over coated on both
27 sides with polyvinylidene chloride (PVDC) in order to allow the
28 bladder to be thermally welded for sealing and encapsulating

1 the inflation material. The inflation bladder is fabricated
2 into the form of an elongated flexible tube in which is
3 disposed an inflation material, such as the sublimation powder.
4 The elongated flexible tubular bladder is then sealed so as to
5 contain the sublimation powder within the inflation bladder.
6 The inflation bladder is inserted between the top and bottom
7 films and then bonded to the top and bottom films and to the
8 left and right frames, for forming the inflatable hinge. The
9 left and right frames provides support for the solar cell
10 panels, stabilizes the flex circuit, provides a rigid support
11 for the inflation bladder, and provides a rigid support for the
12 top film encapsulating the uncured resin. The inflation
13 material is inserted into the bladder prior to thermal sealing.

14
15 The inflation material in the bladder provides a
16 vaporization inflation system. The inflation material can be a
17 powder, a solid, or a liquid inserted into the bladder during
18 fabrication. Sublimation or vaporization of the inflation
19 material will transition the material to the gas phase as the
20 external pressure on the hinge inflation bladder transitions
21 from one atmosphere to the vacuum in space. When the hinge is
22 released when on-orbit in space, the inflation material will
23 continue to transition to the gas phase to maintain equilibrium
24 pressure within the inflation bladder. This pressure provides
25 the mechanical force necessary to inflate the bladder to deploy
26 the hinge and to hold the deployed hinge in the desired
27 deployed position while the ultraviolet sunlight cures the
28 curing resin. The hinge is inflated to approximately one psi.

1 The maximum allowable pressure of the bladders is limited by
2 seam strength. Due to the small radius of the hinge, the hinge
3 can withstand a high pressure. The maximum pressure and
4 temperature for the hinge is at most 22.5 psi at 80°C. The
5 inflation material is preferably a mixture of trimethylpentane
6 and hexane that has a maximum pressure limit of 22.5 psi, has
7 good material compatibility, and is inexpensive. This mixture
8 has a vapor pressure equal to the minimum pressure, 0.5 psi, at
9 -11°C. The low temperature deployment for the hinges is limited
10 to -11°C.

11
12 The size of the hinge can be varied as desired. Using
13 templates for sizing the top and bottom films, the panel
14 angular displacement can be, for example, 41.8 ± 2 degrees. The
15 bottom film is a single layer of film whereas the top film is
16 folded and sealed to form a pocket for the curing resin. The
17 width of the top and bottom films span the length of the
18 cylindrical portion of the bladder bonded to the frames. The
19 top film circumferential length is preferably longer than the
20 bottom film. The difference in the circumferential lengths of
21 the top and bottom films provides the proper angle of the
22 panels upon inflation. The diameter of the hinge is dependent
23 on the maximum stack height of the panels. The circumferential
24 length of the bottom film must be enough to span the stack
25 height of two solar cell panels. The bonding of the bladder,
26 top film, and bottom film to the frames maintains the accuracy
27 of the hinge angle.

28

1 The design of the hinge and the left and right frames
2 should be optimized according to the rotational requirement.
3 The rotational requirement may be, for example, 4 to 60 rpm.
4 Based on the maximum rotational speed requirement and the
5 maximum deflection 1.0 centimeter at an edge of a panel, the
6 section modulus of the hinge should be greater than 7.6×10^{-10}
7 m^4 and the section modulus for the left and right frames should
8 be greater than $1.0 \times 10^{-10} \text{m}^4$. The cured hinge stiffness is
9 sufficient to withstand the centripetal force caused by a
10 spinning satellite system such that the deflection of the hinge
11 is within acceptable geodetic shape limits of a power sphere.
12 The UV rigidization resin material is encased in the top film
13 to mitigate outgassing.

14
15 The hinge can be made of various materials and used to
16 support differing types of panels. In the preferred form, the
17 hinge supports opposing thin film solar cell panels using
18 flexible materials. An adhesive, for example, can be used for
19 bonding together the top and bottom films, left and right
20 frames, and the inflation bladder. The curing resin is
21 preferably an epoxy impregnated S-glass fiber curing resin, but
22 other UV curing resin materials can be used, with or without
23 reinforcing fibers. The cured reinforced resin provides
24 structural rigidity after deployment of the hinge and after
25 exposure to ultraviolet light, such as from the sun, in the
26 case of the power sphere. The curing resin provides flexibility
27 for stowing the hinge in a compressed compact form prior to
28 deployment, and provides structural rigidity after deployment

1 and after UV light exposure when the hinge becomes rigid on-
2 orbit. Once cured on-orbit, the hinge becomes completely rigid
3 and provides zero mechanical backlash.

4
5 The hinge is preferably part of a complete deployment
6 system, including a center column in a power sphere, not shown.
7 The hinges are packed into a small stowage volume prior to
8 launch. The center deployment column can also be an inflatable
9 UV rigidizable isogrid boom consisting of a grid work of UV
10 curable composite tows integrated into an air-tight, UV
11 transparent, thin film. A flex circuit can be integrated into a
12 bladder of the column wall. The center column is flexible in
13 the uncured state for compact z-fold packing. The use of the
14 flex circuit in conjunction with UV rigidizable resin material
15 allows for efficient packing for stowage prior to launch. The
16 length of the center column is sized to the specific geodetic
17 sphere for proper alignment of top and bottom hemispheres.
18 After inflation, UV radiation will cure the resin in the center
19 column to rigidize the center column.

20
21 The invention in a first aspect is directed to a wrap
22 around contact for interconnecting a solar cell panel to a flex
23 circuit. The invention in a second aspect is directed to an
24 inflatable hinge having an inflation bladder containing an
25 inflation material and a film encapsulating a curing resin for
26 rigidizing the hinge after inflation of the inflation bladder
27 and after being cured using UV light passing through a UV
28 transparent coating. The wrap around contact can be used for

1 interconnecting solar cell panels through the inflatable hinge.
2 Those skilled in the art can make enhancements, improvements,
3 and modifications to the invention, and these enhancements,
4 improvements, and modifications may nonetheless fall within the
5 spirit and scope of the following claims.

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